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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY, HARVARD UNIVERSITY.

ON THE MAGNETIC BEHAVIOR OF HARDENED CAST IRON AND OF CERTAIN TOOL STEELS AT HIGH EXCITATIONS.

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During the last few years the use of hardened cast iron for permanent magnets has increased very much, and this material has proved especially useful for such shapes as could not be easily forged from steel without heating the metal red hot a number of times and thus making it magnetically unsatisfactory. Cast-iron magnets are very cheap, and they may be made quite as strong and as permanent as magnets made of the best tool steel, even if in strength, though not in permanence, they fall a little behind magnets made of special "magnet steels." Moreover, and this is sometimes of very great importance, the temperature coefficient [1] of a seasoned cast-iron magnet is usually much smaller than that of a magnet of the same strength made of forged or formed steel. This paper discusses briefly a number of determinations of the permeability of specimens of fairly soft and of glass-hard cast iron of the same kind, under excitations up to about 15,000 gausses,[2] and, for purposes of comparison, considers also some measurements made upon hard and soft Stubs "Polished Drill Rod" and upon hard and soft "Crescent Polished Drill Rod."

The principal apparatus used consisted of a yoke (Figure 1) which weighed about 300 kilograms and was excited by a current (from a storage battery) running through a set of amperemeters in series with

[1] Peirce, These Proceedings, **38** (1903); **40** (1905).

[2] Rowland, Phil. Mag., **46** (1873); Fromme, Ann. d. Phys., **13** (1881); **33** (1888); Stefan, Ann. d. Phys., **38** (1889); H. E. J. G. DuBois, Ann. d. Phys., **31** (1888); **51** (1894); B. Walter, Ann. d. Phys., **14** (1904); Ewing, Magnetic Induction in Iron and other Metals; DuBois, The Magnetic Circuit in Theory and Practice.

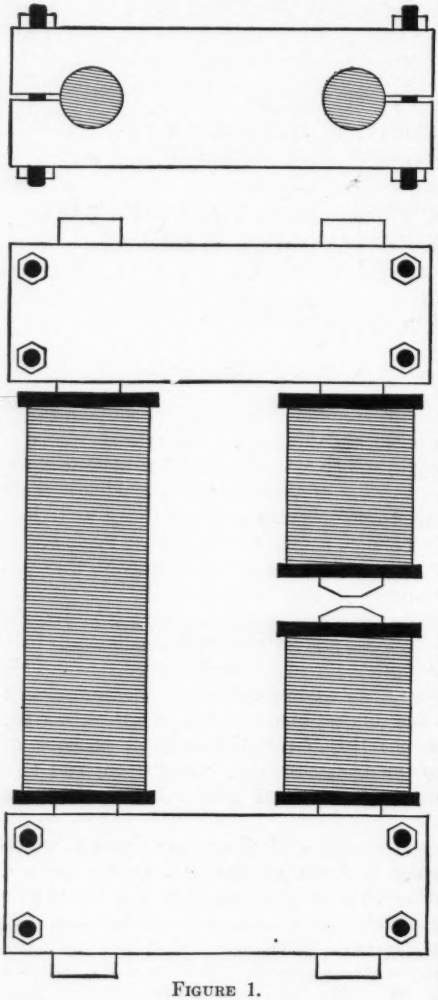

FIGURE 1.

the coil of 2956 turns wound on the spools shown in the diagram. The yoke was furnished with a number of pairs of pole pieces or jaws, to receive specimens of different lengths and shapes. To measure the amount of the induced current in a test coil wound closely upon the piece to be examined, a ballistic galvanometer (V), described in a former paper,[3] was used. The period of this instrument was so long that the throw due to a reversal of the exciting current of the yoke did not appreciably differ from the throw which the same quantity of electricity would have caused if it had been sent instantaneously through the circuit.

The specimens used in the work here described were of two forms. The first form (C, Figure 2) was a cylinder about 1.27 centimeters in diameter and about 15 centimeters long over all, with tapered ends to fit tightly in sockets in the ends of the conical pole pieces of the yoke. The sockets

[3] These Proceedings, **44** (1909).

(G) were first turned out in the lathe and then finished by a reamer made and ground by the machinery afterwards used to cut the tapers on the ends of the test pieces. Each test piece of the hard cast iron had first to be ground to the form of a true cylinder in a universal grinding machine and then to be tapered off at the ends with the help of a centre grinder, mounted motor and all, in the tool post of an engine lathe. All the work was done by Mr. G. W. Thompson, the mechanician of the Jefferson Physical Laboratory, in the most skilful manner, and the reluctance of the joints must have been relatively

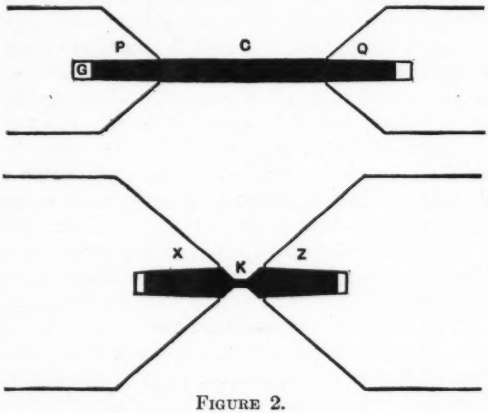

FIGURE 2.

very small. When a specimen of this shape was in position between the pole pieces of the yoke, and a steady current of at least two or three amperes was passing through the exciting coil, it was assumed that the value of H within the small cylinder (C) near the middle of its length was the same as the value of H in the air just outside the metal. The ground of this assumption was a series of experiments carried out some months ago. A piece of homogeneous steel rod about half an inch in diameter and about three hundred and fifty diameters long was placed within a solenoid consisting of 20,904 turns of thoroughly insulated wire wound on a straight piece of stout brass tube about an inch in inside diameter and rather more than sixteen feet long. Near the middle of the steel rod a test coil of fine insulated wire was wound closely on it, and then, with its leads, made thoroughly waterproof, so that a current of tap water could be kept running around the rod in the brass tube to hold the temperature of the steel nearly

constant when strong currents should be sent through the solenoid. The steel was first demagnetized by means of a long series of currents in the solenoid, alternating in direction and steadily decreasing in intensity, and then a series of steady direct currents of carefully measured intensities, each a little stronger than the last, were sent through the solenoid and reversed many times at each stage to determine the corresponding value of B in the steel. In this manner it was possible to get a satisfactory curve of ascending reversals for the steel up to $H = 400$ and $B = 20{,}500$, nearly. The length of the rod was, relative to its diameter, so great that the demagnetizing factor was very small and the correction for the ends very easily made. The rod was then demagnetized again, and the process described was repeated two or three times until the resulting table of B versus H values seemed to be well determined. After this, short pieces of various lengths, cut from the rod which had been tested, were used in the yoke and were mounted in different ways in the hope of discovering some satisfactory method of studying the permeability of the steel by experiments upon these pieces, which should give the same results up to an induction of about 20,000 as those already obtained by the work with the long solenoid. After long trial, a length of cylinder was found which seemed, in this particular yoke, to make the values of H at the centre of the length of the specimen practically the same as the value in the air just outside the metal. Two different materials were used in stout rod form in the long solenoid, Bessemer Steel and "Compressed Steel," an extremely homogeneous kind of steel prepared for us by the Boston Compressed Shafting Company.

In all the cases tried specimens of the size and shape described above seemed to give the same permeability up to values of the induction as great as 20,000 as the long solenoid did, and, for somewhat higher values of B, to yield results which agreed with those obtained, where it first becomes trustworthy, by the "Isthmus Method."

After the central portion of each of these specimens had been covered with an extremely thin coat of varnish, the diameter was determined under the microscopes of a Zeiss Comparator, reading to the nearest thousandth of a millimeter directly. Then two test coils, each of twenty turns of very fine, well-insulated wire, were wound side by side in a single layer over the varnished metal and extended over perhaps a centimeter at the middle of the rod. These coils were tested against each other when the specimen was in the yoke, to see if they were alike, and if they were, both, in series, formed the inner test coil (L) to be used in the measurements. The second testing coil (M) was wound on a very carefully made spool of boxwood which had been seasoning for

many years. This spool kept its diameter practically unchanged during the measurements here recorded, though it shrank very slightly soon

TABLE I.

CYLINDER OF SOFT CAST IRON.

H.	B.	I.	μ.
114	9950	782	87.3
172	10800	846	62.8
433	13900	1070	32.1
744	15750	1200	21.2
1234	17300	1280	14.0
1820	18170	1300	10.0

after it was first made. The diameter of the wood was about 1.9135 centimeters, and that of the outside of the wire of the coil about 1.9591 centimeters, the last figure in each case being, of course, doubtful.

TABLE II.

ISTHMUS OF SOFT CAST IRON.

H.	B.	I.	μ.
12700	31100	1465	2.5
13550	32100	1475	2.4
13800	32500	1488	2.4
15100	33650	1472	2.2

Hard rubber is so susceptible in a magnetic field as to make it impossible to use a spool of this material to support a testing coil. When the specimen was in place between the jaws of the yoke, it was covered by the shorter spools of the yoke.

The value of H in the air just outside the metal was obtained by re-

versing the exciting current of the yoke when L and M were opposed to each other in the circuit of the ballistic galvanometer (V) described

TABLE III.

CYLINDER OF HARD CAST IRON.

H.	B.	I.	μ.
142	7860	614	55.4
254	9700	752	38.2
339	10850	836	30.6
684	13050	983	19.1
915	14050	1044	15.4
1570	15900	1138	10.1
2020	16800	1176	8.3

above. When L alone was used in the galvanometer circuit, and proper corrections for the air lines through L had been made by the use of the H just determined, it was possible to measure the induction flux in the metal.

TABLE IV.

ISTHMUS OF HARD CAST IRON.

H.	B.	I.	μ.
10900	26540	1245	2.4
13200	28600	1226	2.2
14800	30200	1226	2.0

The second kind of specimen shown approximately by K, Figure 2, was of the shape usually employed in isthmus measurements. Cast iron differs from steel in that it can be heated so hot before it is chilled that it becomes eventually hard throughout its mass, while steel can be hardened only for a little distance from the surface. On the other hand,

it is not easy to harden a long slender rod of cast iron without its becoming slightly crooked in the process. An isthmus piece of cast iron has, therefore, to be ground into shape at much labor, from a glass hard

TABLE V.

CYLINDER OF SOFT CRESCENT DRILL ROD.

H.	B.	I.	μ.
122	13060	1030	107.0
209	16730	1315	80.1
272	17190	1351	63.2
486	18400	1425	37.9
783	19150	1462	24.5
1535	20600	1516	13.4
1798	20900	1527	11.6

cylinder. The hardened steel isthmus pieces, on the contrary, were shaped while soft, and were then chilled inside a supporting tube after they had been heated in a gas furnace.

TABLE VI.

ISTHMUS OF SOFT CRESCENT DRILL ROD.

H.	B.	I.	μ.
4860	24600	1570	5.1
7190	27100	1584	3.8
10000	29700	1569	3.0
12020	32500	1629	2.7
13150	33800	1642	2.6

The "Isthmus Method" for determining the permeability of a small piece of magnetic metal at a high excitation rests, of course, upon the assumption that the value of H just without the test piece is equal to

the average value of H over the cross section of the metal at the neck. At the surface of a magnet the tangential components of the magnetic

TABLE VII.

CYLINDER OF SOFT STUBS POLISHED DRILL ROD.

H.	B.	I.	μ.
132	14600	1154	110.6
299	16700	1307	55.8
540	18100	1395	33.5
830	19000	1445	22.9
1380	20200	1495	14.6
1780	20800	1514	11.7

force are continuous, while the normal component is discontinuous: it seems desirable, therefore, before one applies the method in any particular case, that one make sure that the lines of the field in the air space

TABLE VIII.

ISTHMUS OF SOFT STUBS DRILL ROD.

H.	B.	I.	μ.
7900	26800	1500	3.4
13850	33200	1545	2.4
14900	34400	1554	2.3
15800	36200	1570	2.3
17100	37000	1587	2.2

to be used are practically straight and parallel to the axis of the specimen. Any person who has had experience in using large yokes at high excitations, where because of the low permeability of the metal the leakage is very great, knows how slight a change in the shape of a specimen

may alter the field in the neighborhood of the test piece very sensibly. An isthmus piece of steel which had been hardened unequally might warp the field sufficiently to make the observations of the permeability wholly erroneous.

TABLE IX.

CYLINDER OF HARD CRESCENT DRILL ROD.

H.	B.	I.	H.	B.	I.
114	8600	677	850	14650	1097
175	10050	786	1041	15200	1127
254	11300	879	1337	15950	1162
503	13000	993	1894	17000	1200

After much consideration I have decided not to print the results of my measurements upon isthmus pieces of glass-hard Stubs and Crescent Drill Rod for the reason that the maximum values of I seem to be rather too high. In one case, indeed, the effect of hardening an isthmus piece

TABLE X.

CYLINDER OF HARD STUBS DRILL ROD.

H.	B.	I.	H.	B.	I.
123	8600	675	564	13750	1049
180	10020	783	982	15350	1143
256	11300	878	1416	16250	1216

of steel was to make the ultimate value of I rather greater than before, though for moderate excitations the permeability was less. I hope to try soon the effect upon the uniformity of the field about the isthmus of harder jaws. The results obtained with the hard cast iron seem to be good.

The cast iron used for the observations recorded below, which was extremely soft and easy to work, came from the Broadway Iron Foundry

of Cambridgeport, Mass., where we have obtained during the last few years a large number of castings of different forms for permanent magnets which proved when made and seasoned to be very strong and to have remarkably small temperature coefficients.

It will be noticed that this iron while soft is rather more permeable than that which was the foundation for the formula for reluctivity in "Ordinary Dynamo Cast Iron" given by Messrs. Houston and Kennelly in their Electro-Dynamic Machinery, but is very similar so far as

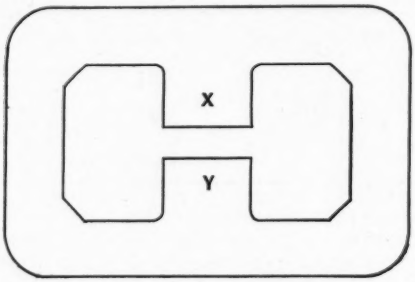

FIGURE 3.

results are available with the standard "Gray Cast Iron" used for the table given in the pamphlet on the "Magnetic Circuit" of the International Textbook Company. Although I had at command a much larger yoke than the one used, no attempt was made to carry the excitation beyond 15,000 gausses. The ultimate value of I in my hardened cast iron was about the same as that which Ewing gives for "Cast Iron" in "Magnetic Induction in Iron and Other Metals," § 93.

The magnetic effects of hardening upon a mass of cast iron are often very noticeable at comparatively low excitations. The two halves of each of two thick castings, one soft, the other very hard, of the form shown in Figure 3, were wound with 156 turns each of insulated wire, and the two coils on each casting were so connected in series that when a current was sent through the circuit both conspired to make one of the projections (say X) a north pole and the other (Y) a south pole. With each of the castings a rude kind of hysteresis diagram was obtained by measuring for different current strengths the values of the induction flux across a definite area in the air gap between the poles. These fluxes plotted against the corresponding currents gave the diagrams shown in Figure 4. The A curve belongs to the soft casting, the

B curve to the hard one. While it would be difficult to explain the exact meaning of these curves in terms of the permeabilities of the iron, the differences are striking.

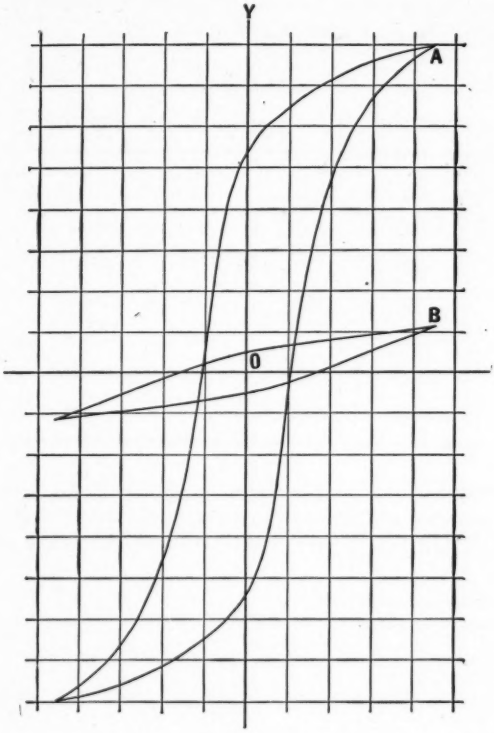

FIGURE 4.

It appears from the observations of Ewing upon Vicker's Tool Steel that in the case of the specimen he used the value of I was still rising, and at a fairly rapid rate, when H grew to be as great as 14,000. The same tendency, it will be noticed, is shown very clearly in the two kinds of steel which I have studied. These were chosen as being perhaps the best annealed brands of fine tool steel to be had in the market.

The very interesting results given in Table XI were obtained by Mr. John Coulson, who has helped me in all this work, with a standard cylinder, 1.283 centimeters in diameter, made of Jessops Tool Steel. This celebrated brand of steel seems harder under the file than the Stubs or the Crescent Drill Rod, but is remarkably permeable, and has been much used for permanent magnets.

TABLE XI.

CYLINDER OF JESSOPS ROUND TOOL STEEL.

H.	B.	I.	H.	B.	I.
110	15250	1205	960	19950	1510
158	16200	1280	1030	20100	1520
255	17450	1370	1200	20450	1530
500	18850	1460	1680	21100	1545
645	19100	1470	1980	21600	1560
810	19700	1505			

My thanks are due to the Trustees of the Bache Fund of the National Academy of Sciences who have kindly lent me some of the apparatus used in making the observations described in this paper.

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